Physica C 469 (2009) 685–688

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Suppression of guidance force decay of HTS bulk exposed to AC magnetic field perturbation in a maglev vehicle system

Longcai Zhang [a,*], Suyu Wang [b], Jiasu Wang [b]

[a] College of Air Traffic Management, Civil Aviation Flight University of China, Guanghan, Sichuan 618307, PR China
[b] Applied Superconductivity Laboratory, Southwest Jiaotong University, P.O. Box 152, Chengdu, Sichuan 610031, PR China

ARTICLE INFO

Article history:
Received 13 August 2008
Received in revised form 15 September 2008
Accepted 14 October 2008
Available online 21 October 2008

PACS:
85.25.−j

Keywords:
HTS bulk
AC magnetic field
Guidance force decay
Maglev vehicle system

ABSTRACT

Superconducting maglev vehicle was one of the most promising applications of HTS bulks. In such a system, the HTS bulks were always exposed to AC external magnetic field, which was generated by the inhomogeneous surface magnetic field of the NdFeB guideway. In our previous work, it was observed that the guidance force of the YBCO bulk over the NdFdB guideway used in the high-temperature superconducting maglev vehicle system was decayed by the application of the AC external magnetic field. In this paper, we adopted a method to suppress the decay by altering the field–cooled height of the bulk. From the experimental results, it was found that the decay rate of the guidance force was smaller at lower field–cooled height. So we could suppress the guidance force decay of HTS bulk exposed to AC external magnetic field perturbation in the maglev vehicle system by reducing the field–cooled height of the bulk. Furthermore, all the experimental results in this paper were explained based on Bean critical-state model.

1. Introduction

Magnetic levitation based on the interaction between a permanent magnet and a HTS bulk have great potential for various engineering applications [1,2], especially in high-temperature superconducting maglev vehicle system [3]. The stability of the system can be achieved without any complex control owe to the pinning effect of the bulks [4]. But in practice, the guideway used in the HTS maglev vehicle system is composed of many NdFeB permanent magnets [5], whose surface magnetic field is not always immutable owe to the effect of airgap between the adjacent magnets. So when the maglev vehicle is running over this guideway, the bulks onboard will be exposed to time-varying external magnetic field perturbations, which is similar to AC magnetic field perturbations.

The guidance force is an important parameter of the HTS maglev vehicle system. Much work had been done to study the trapped field characteristics of the bulk superconductor in time-varying external magnetic field [6,7]. But a few people studied the influence of time-varying external magnetic field on guidance force of the HTS bulk above permanent magnet. In our previous work, we experimentally investigated the influence of AC external magnetic field perturbation on the guidance force of HTS bulk over a NdFeB guideway. From the experiment results, it was found that the guidance force was attenuated with the application of the AC external magnetic filed, and the decay increased with the amplitude of AC field [8]. It was disadvantageous for the application of the superconducting maglev vehicle. Because the stability of the whole maglev vehicle system would be affected owe to the attenuation of the guidance force. So we should make effort to suppress the guidance force decay. In this paper, we carried on an experiment to investigate the relationship between the field–cooled height and the guidance force decay of the bulk exposed to AC magnetic field so as to find a method to suppress the guidance force decay.

2. Experiment

2.1. Equipment

Fig. 1 was a schematic drawing of the experiment system, which was composed of HTS maglev measurement equipment [9], a NdFeB guideway, an electromagnet, and a YBCO bulk.

The HTS maglev measurement equipment included a cylindrical liquid nitrogen vessel, whose bottom wall was a thickness of 3 mm. The measurement process and data acquisition were controlled automatically by a computer. The guideway were composed of two rows NdFeB permanent magnets and three iron yokes which

* Corresponding author. Tel./fax: +86 838 5182513.
E-mail address: zhlcai2000@163.com (L. Zhang).

0921-4534/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2008.10.002

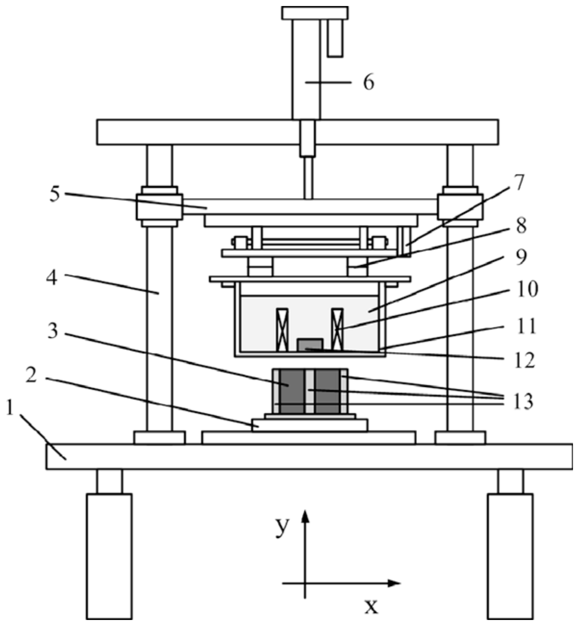

Fig. 1. Schematic drawing of the experiment system (1) base, (2) lateral drive platform, (3) NdFeB guideway, (4) vertical guide way, (5) vertical drive platform, (6) servo motor, (7) guidance force sensor, (8) levitation force sensor, (9) liquid nitrogen, (10) electromagnet, (11) liquid nitrogen vessel, (12) YBCO bulk, (13) iron yokes.

was used for concentrating magnetic flux [5] and the concentrating surface magnetic flux density of the guideway was up to 0.7 T. The electromagnet was composed of solenoid coils wound with copper wires. The outer and inner diameters and the height of coil were 80.0 mm, 45.0 mm, and 40.0 mm. In this experiment, the electromagnet would generate AC magnetic field by applying AC current. The YBCO bulk employed in this experiment was a cylindrical one, 30.0 mm in diameter and 15.0 mm in thickness. When the experiment was performed, the guidance force, which was the level force between the bulk and the guideway in the maglev vehicle system, was detected by the guidance force sensor and the data acquisition was transferred to the HTS maglev measurement system.

2.2. Procedure

In this experiment, we employed the following procedure. Firstly, the YBCO bulk was placed at the center of the electromagnet, and the both were fixed in the liquid nitrogen vessel, which was placed above the permanent magnetic guideway at a certain height. Secondly the vessel was filled with liquid nitrogen at 77 K to let the bulk transit to the superconducting state in the presence of magnetic field generated by the permanent magnetic guideway. We called this process field-cooling (FC). The gap between the bottom of the bulk and the surface of the guideway was field-cooling height (FCH), as shown in Fig. 2. Thirdly, AC external magnetic field generated by the electromagnet was applied to the bulk and the directions were paralleled to the axis of the cylindrical bulk. Finally, moved the vessel along the *x* and *y* axis direction as shown in Fig. 1 and measured the guidance force as a function of time. In this step, the gap between the bottom of the bulk and the surface of the guideway was called work height (WH), and the distance between the center of the bulk and the one of the guideway surface was called lateral displacement (LD), as shown in Fig. 2. In this paper, the FCH was different in each experiment, and all the LD and the WH were kept constant and set to 20 mm and 10 mm, respectively.

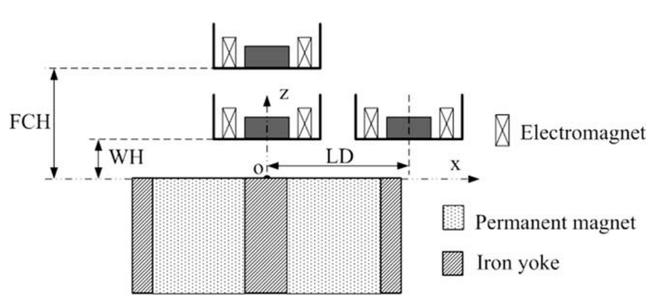

Fig. 2. Schematic drawing of the experimental procedure.

3. Result and discussion

In order to keep the guidance force of the vehicle from being attenuated greatly, we should make effort to find a method to suppress the guidance force decay of the HTS bulk exposed to AC magnetic field perturbation in the maglev vehicle system. In this paper, we tried to achieve the goal mentioned above by altering the FCH of the HTS bulk. In our previous work, we reported that the maximal difference value of the surface magnetic field at the height of 10 mm over the NdFeB guideway was no more than 0.01 T and the guidance force decay was almost independent of the frequency of the AC field [8]. So we employed the following experiment in this paper. AC external magnetic field with different amplitudes B_{ac} and frequency f = 120 Hz was applied to the HTS bulk placed in the liquid nitrogen vessel. The amplitudes B_{ac} were 0.01 T, 0.021 T, 0.033 T and 0.046 T, respectively. The FCH were set to 10 mm, 15 mm and 20 mm, respectively. And the WH and the LD were kept constant and set to 10 mm and 20 mm in all the experiment, respectively.

When the AC field was not applied, the value of the guidance force was called initial value. With the application of the AC magnetic field, the guidance force decayed rapidly. After about 100 s later, the guidance force would relax to achieve stability, and the value of the guidance force at this moment was called stable value, as shown in Ref. [8]. The stable values of the guidance force of the bulk with different field-cooling height were shown in Table 1. From the experiment results, we could conclude that the guidance force decayed with the increase of the amplitude of AC field. In order to investigate the relationship between the FCH and the guidance force decay rate of the bulk exposed to AC magnetic field, we computed the guidance force decay which was obtained by subtracting the stable valve from the initial value. The ratio of the guidance force decay to the initial value was defined as the guidance force decay rate. The relationship between the guidance force decay and the amplitudes B_{ac} of the AC external magnetic field was shown in Table 2. The guidance force decay in the case of zero AC external magnetic field, i.e., only flux creep, was very small and ignored in our experiments.

Fig. 3 showed the guidance force decay rate of the bulk exposed to the AC external magnetic field with the different amplitudes B_{ac}. When the amplitude of AC external magnetic field B_{ac} was in-

Table 1
The value of the guidance force compared with the amplitudes B_{ac} of the AC field.

B_{ac}(T)	Guidance force (N)		
	FCH = 10 mm	FCH = 15 mm	FCH = 20 mm
0	8.42	5.06	3.21
0.011	7.95	4.71	2.92
0.021	7.72	4.47	2.74
0.033	7.47	4.22	2.58
0.046	7.15	3.93	2.38

Table 2
The guidance force decay rate compared with the amplitudes B_{ac} of the AC field.

B_{ac}(T)	Guidance force decay rate (%)		
	FCH = 10 mm	FCH = 15 mm	FCH = 20 mm
0	0	0	0
0.011	5.6	6.9	9.0
0.021	8.3	11.7	14.6
0.033	11.3	16.6	19.6
0.046	15.1	22.3	25.9

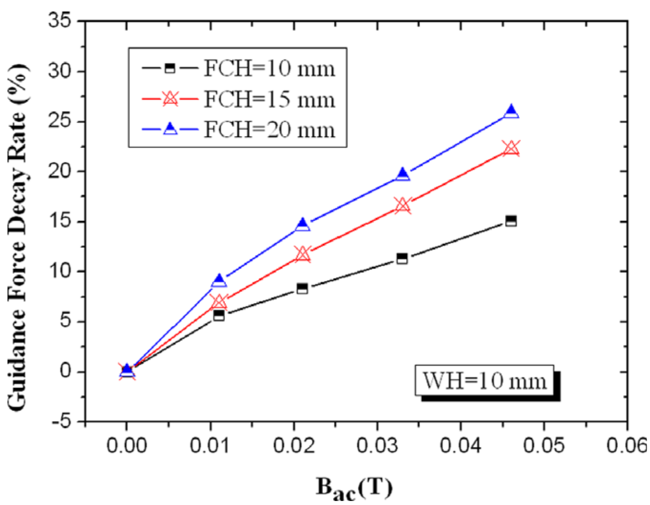

Fig. 3. Experimental results of the guidance force decay rate of the bulk exposed to AC field in the different FCH cases.

creased from small to large, the guidance force decay rate also increased accordingly. The FCH of the bulk were different, so were the guidance force decay rate. Under the condition of the same WH, the higher the FCH was, the more the guidance force decay rate was. As shown in Fig. 3, the guidance force decay rate of the bulk whose FCH was set to 20 mm was the largest. In other words, with the application of the same AC external magnetic field, the guidance force decay rate could be decreased by reducing the FCH of the bulk.

As far as the high-temperature superconducting maglev vehicle system was concerned, the guidance force was an important parameter. When the vehicle was running over the NdFeB guideway, the bulks onboard were exposed to time-varying magnetic field perturbations, which was similar to AC field perturbations in our experiment. The perturbations decayed the guidance force of the bulks and even affected the stability of the whole maglev vehicle system. So based on the experimental results mentioned above, we could suppress the guidance force decay by reducing the FCH of the bulks properly.

According to the Bean critical-state model [10], for an infinitely long superconducting cylinder of radius R subjected to external AC magnetic field of amplitude B_{ac} paralleled to the cylinder axis, the distributions of the trapped magnetic field B and current density J are shown in Fig. 4.

J_c is the critical current density of the bulk. In the initial state, the distributions of the trapped magnetic field and the shielding current in the cylindrical bulk were shown by dashed line in Fig. 4. The YBCO bulk was cooled over the NdFeB guideway, so the more the bulk was closed to the guideway surface, the stronger the trapped magnetic field of the bulk was. Therefore, the trapped magnetic field B_{t0} of the bulk which was cooled at higher FCH was weaker than the trapped magnetic field B_{t0} of the one cooled at lower FCH. When the bulk was exposed to AC magnetic field, the AC filed would penetrate into the cylinder from the surface, and

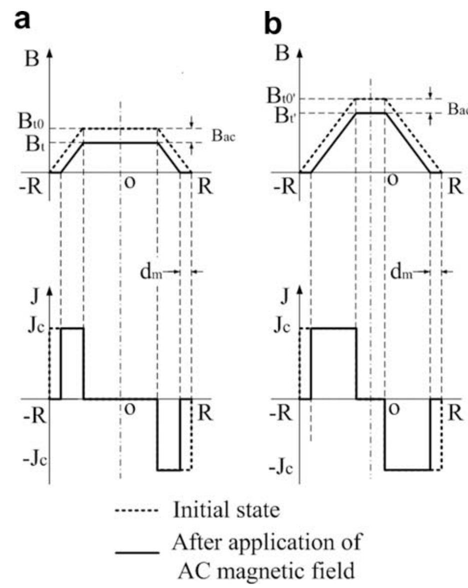

Fig. 4. Distributions of the trapped magnetic field B and current density J in the bulk exposed to AC magnetic field: (a) the bulk was cooled at higher FCH; (b) the bulk was cooled at lower FCH.

the penetration depth of the AC field d_m was given by the following equation [11].

$$d_m = B_{ac}/\mu_0 J_c,$$

where μ_0 is the magnetic permeability in vacuum. Therefore, no matter whether the FCH were equal or not, the trapped penetration depths d_m were always equal owe to the same amplitude B_{ac} of the AC field, as shown in Fig. 3.

When the AC field was decreased gradually to zero, the magnetic field and the shielding currents in the penetration area would become zero [12,13], so the guidance force, which was dependent on the trapped flux [14], would be decreased. The distributions of the trapped magnetic field and the shielding current in the bulk were shown by real line in Fig. 4. The peak values of the trapped magnetic field of the bulk which was cooled at higher FCH and lower FCH were denoted by B_t and B_t in this state, respectively. From the Fig. 4, it was conclude that the tapped magnetic field was decay owe to the application of the AC magnetic field. And the decay rate of the bulk cooled at lower FCH was smaller than the one of the bulk cooled at higher FCH. So the guidance force decay rate of the bulk cooled at lower FCH was also smaller. It was agreement with the experimental results as shown in Fig. 3.

4. Conclusion

We have putted forward a method to suppress the guidance force decay of the bulk exposed to AC magnetic field perturbation over the NdFeB guideway by experiment. The experiment results showed that the guidance force decay rate could be decreased by reducing the FCH of the bulk. All the results were explained based on the Bean critical-state model. So in order to keep the guidance force of the vehicle from being attenuated greatly, we could properly reduce the FCH of the bulks onboard in the maglev vehicle system.

Acknowledgements

All the experimental equipments were supplied by Applied Superconductivity Laboratory, Southwest Jiaotong University, and the authors had benefited from helpful discussions with Pro. Jiasu

Wang. So, we wish to express our gratitude to all parties concerned.

References

[1] J.R. Hull, M. Murakami, et al., Proc. IEEE 92 (10) (2004) 1705.
[2] K.B. Ma, Y.V. Postrekhin, W.k. Chu, Rev. Sci. Instrum. 74 (12) (2003) 4989.
[3] Jiasu Wang, Suyu Wang, Youwen Zeng, Physica C 378–381 (2002) 809.
[4] Ken Nagashima, Yukikazu Iwasa, Koichiro Sawa, IEEE Trans. Appl. Supercond. 10 (3) (2000) 1642.
[5] Longcai Zhang, Jiasu Wang, Qingyong He, et al., Physica C 459 (2007) 33.
[6] Y. Tachi, N. Uemura, Y. Iwasa, et al., Physica C 357–360 (2001) 771.
[7] Alvaro Sanchez, Carles Navau, Physica C 364–365 (2001) 360.
[8] Longcai Zhang, Suyu Wang, Jiasu Wang, et al., Physica C 467 (2007) 96.
[9] S.Y. Wang, J.S. Wang, C.Y. Deng, et al., IEEE Trans. Appl. Supercond. 17 (2) (2007).
[10] C.P. Bean, Phys. Rev. Lett. 8 (1962) 250.
[11] Y. Zushi, I. Asaba, J. Ogawa, et al., Cryogenics 45 (2005) 17.
[12] K. Yamagishi, J. Ogawa, O. Tsukamoto, et al., Physica C 392–396 (2003) 659.
[13] J. Ogawa, M. Iwamoto, K. Yamagishi, et al., Physica C 386 (2003) 26.
[14] Jiasu Wang, Suyu Wang, Zhongyou Ren, et al., IEEE Trans. Appl. Supercond. 13 (12) (2003) 2154.